Mission Considerations for Future MEO SAR Systems

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Abstract

Low Earth Orbit Synthetic Aperture Radar (LEO SAR) systems, at altitudes below 1000 km, have a limitation in regard to their instantaneous coverage on Earth and their long revisit time to the areas of interest. A suggested way to overcome these limitations is to go towards higher orbital altitudes. Increasing orbital altitude towards medium Earth orbit (MEO) heights, at altitudes varying from 2000 to 35768 km, provides advantages with respect to spatial coverage, global temporal revisit times and communications infrastructure. This paper discusses various design aspects of MEO SAR missions. It presents the main challenges in performance and shows they can be overcome for moderate resolution systems. It then describes the ability of MEO SAR to provide global coverage in 1- to 2-day revisit or continental/oceanic coverage with multi-daily observations, making MEO SAR very attractive for future scientific missions with specific interferometric and polarimetric capabilities.

1 Introduction

Current LEO SAR technology faces severe challenges to deliver short revisit times (e.g., daily) and wide swaths (e.g., 1000 km). The obvious way to improve those is to complicate the radar payload and operation, and launch two or more twin satellites systems working in a constellation like in the case of Sentinel-1 [1], Cosmo-SkyMed [2], TerraSAR-X/TanDEM-X/Paz [3], or IRIS E10 proposal [4].

With the current advancements in technology and the feasibility of building bigger SAR antennas, research started deviating towards studying higher Earth orbital altitudes up to geostationary orbital heights. MEO SAR systems fall in between lower and higher altitude orbits; potentially able to make the best of the other two options, while overcoming the previously mentioned limitations. MEO SAR is able to perform with high PRF, providing large swaths and global scale polarimetric measurements with repeats as short as 3 days, and continental coverage within 1 day.

The main challenge for high altitude SAR systems is to deliver acceptable sensitivity with the current technology. Following the available literature [5, 6, 7, 8], this paper provides a discussion on the relevant changes experienced by a SAR system at MEO altitudes, and gives a clear path for the selection procedure of a suitable MEO SAR system through descriptive plots and tables.

The structure of the paper is as follows. Section 2 discusses the sensitivity and orbit consideration aspects, including revisit, coverage, radiation environments and launch costs. Section 3 provides an example of a MEO SAR mission at around 6000 km with specific interferometric capabilities. The paper is ended with an outlook.

2 Orbit Selection Strategy

The selection of the orbit plays a fundamental role in the performance of the system and its ability to fulfill observation and mission requirements. In this section, we will analyze the trade-off space concerning sensitivity, revisit, coverage, radiation and marginal cost drivers.

2.1 Sensitivity considerations

The sensitivity of a SAR system is characterized by the NESZ figure, i.e., the value of the backscatter coefficient σ_0 corresponding to a signal-to-noise ratio of unity. The value of the NESZ depends naturally on the altitude of the spacecraft. For an orbital height under analysis (e.g., MEO), the variation (in dB) of the NESZ can be approximated by

$$\Delta\mathrm{NESZ} \approx 3 \cdot \Delta R + \Delta L_{\mathrm{a}} - (\Delta G_{\mathrm{tx}} + \Delta G_{\mathrm{rx}}), \quad (1)$$

where all factors are given in dB with respect to a reference orbital height (e.g., LEO), and any change in the transmitted power and resolution are ignored for the moment. The first factor represents the change in the slant range ΔR. The factor ΔL_{a} accounts for a change in the azimuth length of the antenna. Let us recall the expression of the azimuth resolution of a SAR system

$$\delta_{\mathrm{az}} = \frac{L_{\mathrm{az}}}{2} \cdot F_{\mathrm{az}} = \frac{L_{\mathrm{az}}}{2} \cdot \frac{v_{\mathrm{g}}}{v_{\mathrm{s}}}, \quad (2)$$

where v_{g} and v_{s} are the ground and orbital velocities, respectively. The factor F_{az} decreases with altitude, which partially -but not fully- compensates the free-space propagation losses increase for MEO. If the azimuth resolution is to be maintained, we can substitute ΔL_{a} by $-\Delta F_{\mathrm{az}}$. For a monostatic system, the change in the gain is proportional to the change in the antenna area, i.e.,

$$\Delta G_{\mathrm{tx}} + \Delta G_{\mathrm{rx}} \approx 2 \cdot (\Delta L_{\mathrm{a}} + \Delta L_{\mathrm{e}}), \quad (3)$$

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where ΔL_e represents the change in the elevation dimensions of the radar antenna, which can be further approximated as

$$\Delta L_\mathrm{e} \approx \Delta R - \Delta W_\mathrm{s}, \tag{4}$$

where ΔW_s represents the change in the covered swath. The general simplified form of the change in the NESZ with altitude is

$$\Delta\mathrm{NESZ} \approx \Delta R + \Delta F_\mathrm{az} + 2 \cdot \Delta W_\mathrm{s}. \tag{5}$$

Exploiting the complete potentials of a MEO system, requires the coverage of a swath wider than LEO systems, going with the increased available access area for the same observation geometry. To have a fair comparison in terms of sensitivity, we calculate the cost in ΔNESZ per swath increase, i.e. ΔNESZ for a constant power density, explicitly assuming that the coverage of an increased swath is governed by an increase in the transmit power, proportional to ΔW_s, resulting in a total change in the NESZ

$$\Delta\mathrm{NESZ} \approx \Delta R + \Delta F_\mathrm{az} + \Delta W_\mathrm{s}. \tag{6}$$

Figure 1 shows 6 for an incident angle range [20° − 47°] and a reference LEO height of 500 km.

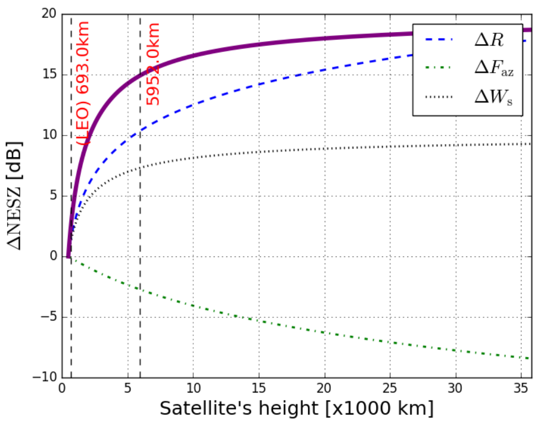

Figure 1: NESZ variation with altitude, assuming power compensation for increased swath, with respect to a reference height of 500 km.

If we assume that the systems under comparison have the same resolution and swath width ($\Delta W_\mathrm{s} = 0$), then the antenna is allowed to grow in both azimuth and elevation with the increasing altitude to maintain the two values constant. Figure 2 shows the corresponding ΔNESZ evaluated for 33° incidence and a reference LEO height of 500 km. NESZ deteriorates by 7.71 dB at around 6000 km and reaches a saturated value of 9.5 dB at higher MEO altitudes, compared to a reference system at 500 km altitude. Compared to a system at 693 km, like Sentinel-1, the MEO loss around 6000 km becomes 6.5 dB. Assuming an incident angle range [20° − 47°], complete coverage of the accessible swath ($\Delta W_\mathrm{s} \neq 0$) results in an additional 12 dB loss in sensitivity (from 693 km to MEO 5952 km orbit) caused by a factor 4 increase in the swath width.

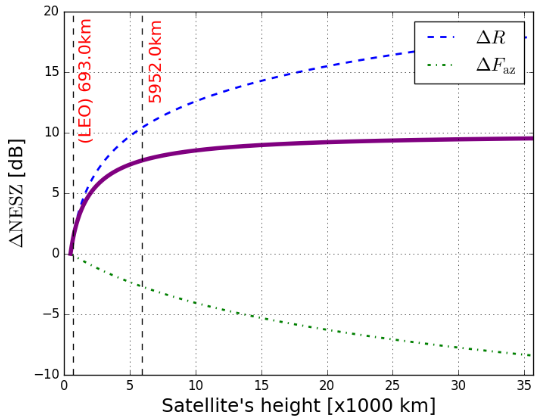

Figure 2: NESZ variation with altitude with respect to a reference height of 500 km.

The conclusion is clear: MEO SAR offers the increase in imaged swath and improved revisit, at the cost of a relevant sensitivity loss, which can be compensated with transmitted power or resolution. The gain in transmit power is bounded by technology, in the short term probably to about 3-4 dB. The gain in the range resolution is somewhat coupled to the azimuth resolution from the design perspective, and provides 3 dB gain for a reduction by a factor 2. The gain in azimuth resolution is limited by the antenna size according to (2), which is again bounded by current technology, probably to about 30 m reflector antenna diameters.

Further possibilities to improve the power budget include the use of reflector antennas, Scan on receive (SCORE) in order to boost the antenna gain for all points along the swath, and operation modes suitable for wide swath systems. An example of wide swath modes is ScanSAR which sacrifices azimuth resolution for NESZ gain. ΔNESZ is improved, due to the gain increase in elevation, by 6 dB for each reduction in the swath width by a factor 2 according to (5). In terms of sensitivity, ScanSAR is more efficient than physically increasing the antenna size, providing twice the gain for the same moderate azimuth resolution, while maintaining a non challenging antenna size. This makes MEO SAR more suited for moderate resolution systems, fitting for the observation of many physical phenomena.

2.2 Optimal orbit selection

We of course focus our analysis on repeat ground track (RGT) orbits, which allow the schedule of measurements on routine bases. Sun-synchronous repeat orbits are a special case of RGT orbits, in which the precession rate of the orbit is equal to the mean motion of the Earth around the sun. For low MEO altitudes below 6000 km, sun-synchronous orbits exist with increasing inclinations, which poses a limitation to deliver global coverage, but provides the observation geometry with sensitivity to North-South displacements, in our opinion one of the -if not the- major singularities of MEO SAR systems. This sensitivity opens the door to true 3-D defor-

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mation measurements, a feature which requires at least two spacecrafts in LEO systems [9]. Beyond 6000 km, sun-synchronous orbits do not exist anymore. Observations conducted in non-sun-synchronous RGT orbits, subject to periods of sidereal days (23 hrs 56 min 4.1 s), are shifted about 4 min/day. Whether this might introduce relevant systematic components in the physical phenomena under observation should be the matter of a detailed analysis for the MEO SAR mission under consideration.

The coverage requirement which supports a vast range of applications is that providing global coverage in the shortest time possible. By following this approach and setting a limit on our incident angle range, we can find a suitable combination of orbital altitude and repeat duration for our mission. If we assume an incident angle limit of [20°, 47°], we can find that equatorial coverage can be achieved in at least 3 days (ascending or descending track) and an orbital altitude window of 2000 km to 8000 km. By selecting this window, we simulate the continuous coverage percentage (between 2 latitudes) provided by each RGT orbit, shown in Figure 3. MEO can also provide local continental coverage within 1 day. As an example, the "1/2 RGT" orbit at about 20000 km repeats twice a day and covers Europe with a $[20° - 45°]$ incidence. At similar heights it is possible to design missions covering other continents or oceans with twice a day revisit.

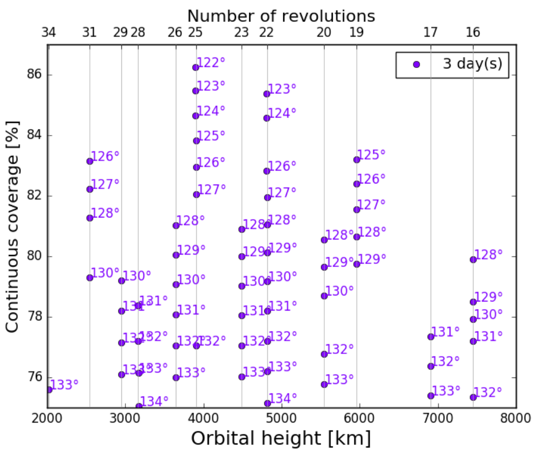

Figure 3: Continuous coverage percentage (oceans & continents) with orbital inclination provided by 3 days RGT orbits for $[20° - 47°]$ incidence (ascending track).

Space radiation, specifically, ionizing radiation, can cause serious damage to payload electronics. For the altitude window [2000 km - 8000 km], we have a major radiation contribution of the inner Van Allen belt starting at the top of the atmosphere and ending at around 6500 km with a peak radiation at around 3500 km, and a minor contribution of the outer belt which starts at around 10000 km. Increased radiation requires thicker shielding, leading to a significant weight and cost increase. For this reason we select our orbit in the radiation gap region, where using an increased aluminum shield thickness of $6\,\mathrm{g/cm^2}$ can reduce the radiation to LEO-like levels. The increase in weight for shielding a 0.5 $\mathrm{m^3}$ cube payload may be of some two-three hundred kg, and it is not perceived as a technological challenge for future MEO SAR missions [10, 11, 12].

On the one hand, a MEO system experiences an increase in the total weight caused mainly by the bigger antennas, thicker radiation shields, and higher transmit power; which in turn requires larger solar panels, batteries and heat dissipation mechanisms. On the other hand, it faces a decrease in the payload capabilities of the launcher. The mass-to-orbit capability of a launcher depends mainly on the latitude of the spaceport, the altitude of the target orbit and its inclination. To estimate the approximate payload mass decrease, we assume that the different orbits are reached by launching from a circular low Earth park orbit, at an altitude h_{ref}, through a Hohman transfer orbit (HTO) to reach the designated circular orbit [13]. Figure 4 shows the loss of payload mass for launching from a park orbit at 185 km to various orbital altitudes within the same orbital plane, using a single HTO and different exhaust velocities for typical launchers in vacuum. At around 6000 km we have a 35-40% mass loss compared to LEO systems. An extra 4-6% loss is expected if a 27-28° orbital inclination change is required (comparing polar to more inclined orbits). This total loss is not considered to be a limiting factor for a MEO mission, especially if we keep in mind the fast evolution of launcher capabilities and re-usability modes, in addition to the possibility of using electric propulsion systems which can provide higher exhaust velocities and further reduce the mass loss for going towards higher altitude orbits.

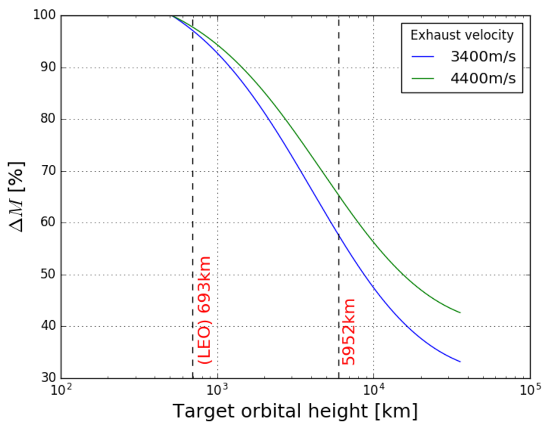

Figure 4: Payload loss for going to higher orbital altitudes within the same orbital plane, via a HTO, from $h_{\mathrm{ref}} = 185\,\mathrm{km}$. 100% is at 512 km (orbital height of TerraSAR-X).

3 Exemplary MEO SAR Mission Scenario

In this section, we will define an exemplary MEO SAR mission using the information of Section 2. To enhance the illustrative power of the example, we will compare the resulting MEO SAR mission to a well-known state-of-the-art LEO constellation, ESA's Sentinel-1 system [1]. The authors are aware the design of an optimized MEO SAR mission would require a more elaborated approach as the one presented here. Nevertheless, we believe this dialectical representation offers a simplified way to illustrate the potentials of MEO SAR missions. According to Figure 3, the "3/19 RGT" orbit at 5952 km, with an inclination of 125°, provides the highest continuous coverage in the radiation gap zone. Figure 5 shows the ascending coverage of such an orbit, where the range of incident angles [20°, 47°] provides enough overlap between consecutive swaths.

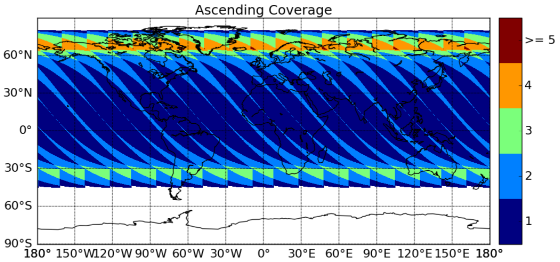

Figure 5: Ascending coverage of a "3/19 RGT" with an access range between 20 and 47 deg (right looking).

Three Sentinel-1 modes are used as reference for our exemplary MEO system: a) the stripmap mode (SM) with 80 km swaths and a resolution $\delta_{az} \times \delta_{gr}$ = 5 m×5 m, b) the interferometric Wide-swath mode (IW) with a 250 km swath and $\delta_{az} \times \delta_{gr}$ = 20 m×5 m, and c) the Extra Wide-swath mode (EW) with a 410 km swaths and $\delta_{az} \times \delta_{gr}$ = 40 m × 20 m. Sentinel-1 uses around 370 W of average power for the SM and IW modes and around 200 W for the EW mode, and achieves a NESZ better than -22 dB in each of the 3 modes [1]. As already hinted, the system parameters of the suggested "3/19 RGT" MEO SAR are then designed to provide similar performance and observation capabilities. A 22-m parabolic reflector with scan-on-receive capabilities and the parameters listed in Table 1 has been designed for the system.

Parameter	Value
Diameter	22 m
Focal length	19.8 m
Offset (elevation)	0 m
Frequency	5.405 GHz
Azimuth elements/channels	2/1
Elevation elements/channels	120/120
Element spacing	0.66 λ
Feed tilt angle	0°
Feed array size	4.33 m × 0.07 m

Table 1: Antenna parameters used in the simulation.

Similar modes A/B/C (one in stripmap, the other two in ScanSAR)have been considered for the exemplary MEO mission. A target NESZ of -22 dB is used for all modes, which requires an increase of average power. The resulting performance of each mode is displayed in Table 2. Compared to Sentinel-1, the MEO system offers an increase between 2 and 3 times in imaged swath, a revisit of three days instead of twelve, and sensitivity to the North-South component of the deformation due to the inclination of the orbit, all this for 1 to 2 dB increase in transmitted power and usage of a big reflector antenna with SCORE capabilities. However, in order to exploit the full potential of higher orbits, the system should be covering the complete incident angle span (here [20°, 47°]) which provides global coverage. The exemplary analysis suggests that the MEO system can achieve this with a resolution in the order of a few tens of meters, for e.g., mode D with $\delta_{az} \times \delta_{gr}$ = 55 m × 40 m, and moderate power might be better suited for deformation monitoring tasks than contemporary LEO missions.

4 Outlook

This paper provides a discussion on relevant trade-offs to be addressed in the design process of a MEO SAR mission, including system aspects and costs. The intrinsic challenges in the MEO SAR power budget can be overcome if moderate-resolution systems, e.g., tens of meters, are in view. The analysis describes the ability of MEO SAR to provide global coverage with 1- to 2-day revisit, or continental/oceanic coverage with multi-daily observations, which shows a clear potential for missions targeting land applications such as soil moisture and crop monitoring. Moreover, a specific advantage of MEO SAR is the sensitivity to the North-South components of deformation, which coupled with a significantly improved revisit opens the door to true 3-D motion and deformation estimates hardly available to monostatic LEO systems [9] for a variety of physical phenomena, including earthquakes, volcanos and landslides monitoring.

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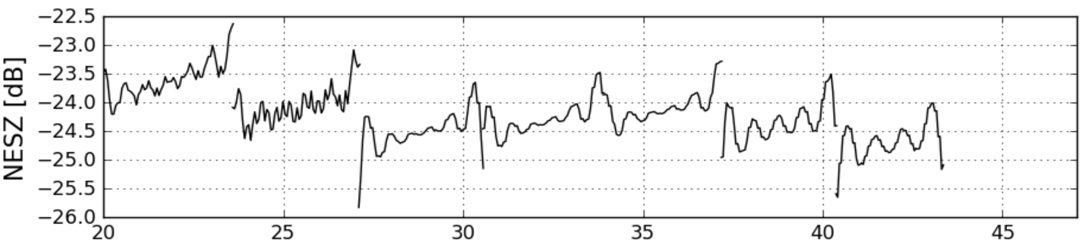
Parameter	Mode A (Stripmap)	Mode B (ScanSAR)	Mode C (ScanSAR)	Mode D (ScanSAR)
Average power	500 W	500 W	300 W	150 W
Total losses	3.2 dB	3.2 dB	3.2 dB	3.2 dB
Noise temperature	465 K	465 K	465 K	465 K
System bandwidth	42-88 MHz	65-88 MHz	11-22 MHz	5-11 MHz
PRF	910 - 1250 Hz	950 - 970 Hz	945 - 970 Hz	1280 - 1355 Hz
Duty cycle	8%	8%	8%	8%
Resolution (az x rg)	5 m x 5 m	20 m x 5 m	40 m x 20 m	55 m x 40 m
Swath width	205 - 110 km	612 km	1419 km	1670 km
Incident angles	20° - 47°	20° - 35.6°	20° - 43.35°	20° - 47°
NESZ	<-22 dB	<-22 dB	<-22 dB	<-22 dB
TASR	<-25 dB	<-25 dB	<-25 dB	<-25 dB

Table 2: Performance values of the suggested exemplary 3/19 RGT MEO SAR mission in different modes.



(a) Mode C

(b) Mode D

Figure 6: Noise equivalent sigma zero plots of (a) mode C and (b) mode D.

